

Coupled-channels analyses for heavy-ion fusion reaction and quasielastic scattering around the Coulomb barrier

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論文目次

1 Introduction	4
2 Heavy-ion Collision Around the Coulomb Barrier	10
2.1 Introduction	10
2.2 Fusion Reaction	11
2.2.1 Experimental Method	11
2.2.2 Evaporation residue detection	13
2.2.3 Fission detection	19
2.3 Large Angle Quasi-elastic Scattering	19
2.3.1 Experimental method	19
2.4 Formal theory of scattering	23
2.5 Coupled-Channels formalism	26
2.5.1 Coupled-channels equation with full angular momentum	26
2.5.2 Coupled-channels equations in the no-Coriolis approximation	30
2.6 Coupling to low-lying collective states	33
2.6.1 Vibrational coupling	33
2.6.2 Rotational coupling	39
2.6.3 IBM coupling	42
2.7 Transfer reaction	43

3 Barrier distribution for heavy-ion fusion reaction and quasi-elastic scattering	45
3.1 Fusion reaction	46
3.1.1 Barrier distribution representation	46
3.1.2 Extracting from experimental data	50
3.1.3 Advantage of barrier distribution analysis	52
3.2 Quasi-elastic scattering	55
3.2.1 Barrier distribution representation	55
3.2.2 Scaling property of quasi-elastic barrier distribution	59
3.2.3 Extracted from experimental data	61
4 Effect of transitional shape and shape admixture on the heavy-ion fusion reactions at sub-barrier energies	63
4.1 Present status of coupled-channels calculations	65
4.2 Parametrization of the interaction	66
4.3 Probe of a transitional structure of ^{74}Ge	67
4.4 Probe of shape admixture in the ground state of ^{72}Ge	70
5 Effects of anharmonic vibration on large angle quasi-elastic scattering of $^{16}\text{O}+^{144}\text{Sm}$	73
5.1 Anharmonicities in nuclear vibrations	74
5.2 Coupled-channels formalism for anharmonic vibration	76
5.2.1 Coupling to anharmonic vibrator	77
5.2.2 Coupling to octupole mode	79
5.3 $^{16}\text{O}+^{144}\text{Sm}$ reaction : Comparison with experimental data	81
5.3.1 Present status of coupled-channels calculations for large angle quasi-elastic scattering of $^{16}\text{O}+^{144}\text{Sm}$	81
5.3.2 Effect of anharmonicities of nuclear vibrations in ^{144}Sm	83
5.3.3 Effects of proton transfer reactions	87
5.3.4 Discussions	93
6 Coupled-channels analysis for large angle quasi-elastic scattering in massive systems	94
6.1 Comparison With experimental data:effects of multi-Phonon excitations	94
6.1.1 Effect of double phonon excitations	97
6.1.2 Effect of triple phonon excitations	102
6.1.3 Surface diffuseness of the nuclear potential	106
7 Summary and concluding remarks	109
A Ion-ion potential	114
A.1 Phenomenological potential	114
A.2 Energy density formalism	116

B Sub-barrier fusion cross section with energy density formalism	121
B.1 Introduction	121
B.2 Coupled-channels calculations with EDF	122
B.3 Effect of incompressibility	126
B.4 Discussions and further perspectives	127
C Numerical stabilization of coupled-channels calculation for large angle quasi-elastic scattering	129

論文内容要旨

The effect of channel couplings, that is, the coupling of the relative motion between the colliding nuclei to their intrinsic motions as well as transfer processes has been by now well known in heavy-ion collisions around the Coulomb barrier. These channel couplings replace a single barrier with many distributed barriers. In the fusion reaction, this barrier distribution can be extracted by taking the second derivative of the product of the center of mass energy, E , and the fusion cross section, σ_{fus} , with respect to E , i.e., $D^{\text{fus}} = d^2(E\sigma_{\text{fus}})/dE^2$ and many experiments have been performed for that purpose.

A similar barrier distribution can also be obtained from the quasi-elastic scattering (a sum of elastic, inelastic scattering and transfer process) at backward angles. Fusion and quasi-elastic scattering are related to each other because of flux conservation, i.e., the fusion is determined by the penetration probability while quasi-elastic scattering by the reflection probability. The quasi-elastic barrier distribution is defined as the first derivative of the ratio of the quasi-elastic to Rutherford cross sections with respect to the energy, i.e. $D^{\text{qel}} = -d(d\sigma_{\text{qel}}/d\sigma_R)/dE$. Although there have been many studies on the properties of the fusion barrier distribution, D^{fus} , the theoretical investigation on the quasi-elastic barrier distribution, D^{qel} , has been rather scarce. The purpose of this thesis is to study the properties of the quasi-elastic barrier distribution in comparison with the fusion barrier distribution. The applicability of the barrier distribution concept in massive systems is also investigated.

A theoretical framework to describe the channel coupling is first reviewed. The coupled channels formalism is introduced using the so-called no-Coriolis approximation which reduces its dimensions. The method to solve the coupled-channels equations for heavy-ion fusion reaction and quasi-elastic scattering is formulated.

The coupled-channels equations are then applied to heavy-ion fusion reactions at sub-barrier energies. This aims at studying whether an analysis of fusion barrier distribution can probe the structure of $^{72,74}\text{Ge}$. We discuss the possibility to probe the transitional shape of ^{74}Ge through the fusion reaction of $^{74}\text{Ge} + ^{74}\text{Ge}$. We also discuss the effect of shape admixture in the ground state of ^{72}Ge on the fusion of $^{72}\text{Ge} + ^{72}\text{Ge}$.

We next apply the coupled-channels formalism to the large-angle quasi-elastic scattering. We first investigate the effects of anharmonic vibration in ^{144}Sm on $^{16}\text{O} + ^{144}\text{Sm}$ scattering. The same coupling schemes which were previously used to explain the experimental fusion cross section and barrier distribution for the same system is employed. It is shown that the anharmonic excitations in ^{144}Sm play an important role in the description of experimental quasi-elastic cross section, although the quasi-elastic barrier distribution

has a distinct high energy peak which is somewhat smeared in the experimental barrier distribution. The effect of proton transfer reaction on this system is also discussed. We suggest that the experimental data for the barrier distributions of fusion reaction and quasi-elastic scattering can not be accounted for simultaneously with the standard coupled-channels approach.

Finally, we carry out a detailed coupled-channels analysis for large-angle quasi-elastic scattering in massive systems. We perform a systematic study on the effects of multi-phonon excitations on the quasi-elastic cross sections as well as the barrier distributions for ^{48}Ti , ^{54}Cr , ^{56}Fe , ^{64}Ni , and $^{70}\text{Zn} + ^{208}\text{Pb}$ reactions. The present coupled-channels calculations well account for the overall width of the experimental barrier distribution for these systems. In particular, it is shown that the calculations taking into account single quadrupole phonon excitation in ^{48}Ti and triple octupole phonon excitations in ^{208}Pb reasonably well reproduce the experimental quasi-elastic cross section and barrier distribution for the $^{48}\text{Ti} + ^{208}\text{Pb}$ reaction. On the other hand, ^{54}Cr , ^{56}Fe , ^{64}Ni , and $^{70}\text{Zn} + ^{208}\text{Pb}$ systems seem to require the double quadrupole phonon excitations in the projectiles in order to reproduce the experimental data.

論文審査の結果の要旨

クーロン障壁近傍のエネルギー領域における重イオン核融合反応では、散乱核の構造（励起）が反応に強い影響を及ぼし、反応確率が著しく変化することが知られている。近年、この効果を「クーロン障壁の分布」という形で表わすことによって重イオン核融合反応の反応機構を理解するという方法が確立し、様々な系における解析が進んでいる。ところが、核融合反応を用いた解析では、核融合反応断面積の2階微分が必要となるため、実験データを精密に測定する必要がある。従って、このような解析は超重核合成反応や不安定核ビームを用いた実験では困難なものになっている。そこで最近注目されているのが、準弾性散乱を用いた障壁分布の解析法である。準弾性散乱は、障壁の透過と反射という意味で核融合反応と相補的であり、また、実験的にも核融合反応に比べて容易なものになっている。核融合障壁分布法が確立しているのに対し、準弾性散乱障壁分布法はまだ発展途上の段階であり、系統的な理論的及び実験的研究が必要とされてきた。特に、核融合障壁分布と準弾性散乱障壁分布の類似性は、これまで基底状態と強く結合する励起状態が存在する場合には示されていたが、弱く結合する多数の状態がある場合に同様の類似性があるかどうかは明らかではなかった。また、超重核合成反応のような重い系においても障壁分布の考えが成り立つのかどうかこれまで知られていなかった。

本研究では、結合チャンネル法を用い、 $^{16}\text{O}+^{144}\text{Sm}$ 系、及び超重核合成反応である ^{48}Ti , ^{54}Cr , ^{56}Fe , ^{64}Ni , ^{70}Zn + ^{208}Pb 系における準弾性散乱断面積及び準弾性散乱障壁分布の詳細な解析を行った。特に、 ^{144}Sm 原子核の2重フォノン状態の非調和性の効果及び超重核合成反応における散乱核の多重フォノン励起の影響に関する議論を行った。

本研究によって、(1) 非調和性2重フォノンのような結合が比較的弱い場合にも核融合障壁分布と準弾性散乱障壁分布の類似性が成り立つこと、(2) それにも関わらず $^{16}\text{O}+^{144}\text{Sm}$ 系においては核融合障壁分布と準弾性散乱障壁分布の実験データは若干異なる振る舞いを示しており、それは現在標準的に用いられている結合チャンネル法の改良が必要であることを示唆していること、(3) 超重核領域のような重い系においても、適当な励起状態を考慮すると準弾性障壁分布の実験データが再現できること、が示された。これらの研究成果は準弾性散乱障壁分布法の有効性を明確に示すものであり、今後この分野の研究に大きく寄与するものである。

審査論文は著者が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。従って、Muhammad Zamrun F. 提出の博士論文は、博士（理学）の学位論文として合格と認める。